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Heavy-ion-fusion-science: summary of US progress

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Abstract
Over the past two years noteworthy experimental and theoretical progress has been made towards the top-level scientific question for the US programme on heavy-ion-fusion-science and high energy density physics: ‘How can heavy-ion beams be compressed to the high intensity required to create high energy density matter and fusion conditions?’ New results in transverse and longitudinal beam compression, high-brightness transport and beam acceleration will be reported. Central to this campaign is final beam compression. With a neutralizing plasma, we demonstrated transverse beam compression by an areal factor of over 100 and longitudinal compression by a factor of >50. We also report on the first demonstration of simultaneous transverse and longitudinal beam compression in plasma. High beam brightness is key to high intensity on target, and detailed experimental and theoretical studies on the effect of secondary electrons on beam brightness degradation are reported. A new accelerator concept for near-term low-cost target heating experiments was invented, and the predicted beam dynamics validated experimentally. We show how these scientific campaigns have created new opportunities for interesting target experiments in the warm dense matter regime. Finally, we summarize progress towards heavy-ion fusion, including the demonstration of a compact driver-size high-brightness ion injector. For all components of our high intensity campaign, the new results have been obtained via tightly coupled efforts in experiments, simulations and theory.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Much progress has been made over the past two years, in experiments, in theory and in simulations, towards the top-level scientific question for the US programme on heavy-ion-fusion-science (HIFS) and high energy density physics (HEDP): ‘How can heavy ion beams be compressed to the high intensity required to create high energy density matter and fusion conditions?’ [1]. This question is central to our near-term programme to explore the warm dense matter regime for HEDP, as well as our long-term quest for heavy-ion fusion.

The warm density matter (WDM) regime has a high scientific discovery potential [2, 3] for the properties of plasmas at high densities ($\sim$0.1–10 g cm^{-3}) and pressures and at moderate temperatures ($\sim$1 eV) in which the Coulomb interaction energy between neighbouring ions exceeds the

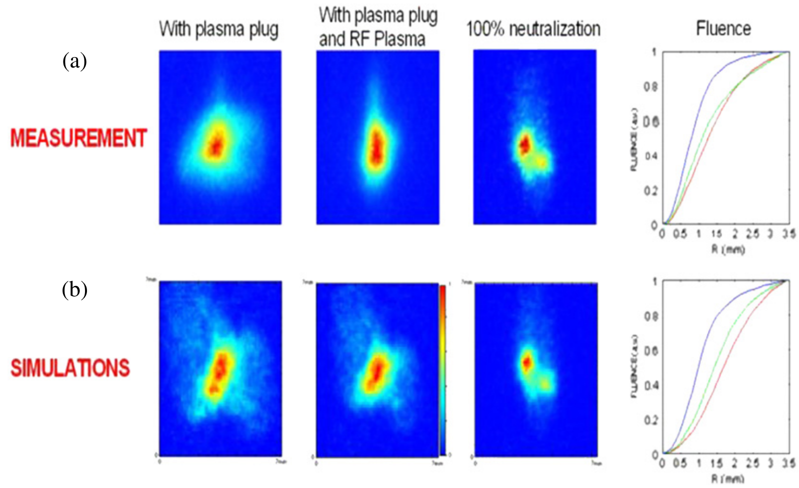

Figure 1. Beams have been compressed from an initial FWHM of 4 cm to about 2 mm, in a metre-long drift tube using techniques of plasma neutralization. The spot sizes were measured, using three different neutralization techniques (*a*) and compared with 3D PIC simulations (*b*).

temperature *kT*. These strongly coupled plasmas are difficult to study analytically and by numerical simulation. Many astrophysical systems (e.g. regions within low mass stars and giant planets) and inertial fusion plasmas in the beginning stages of compression fall in this regime. Although there are other techniques to generate WDM conditions, the method of heating matter with ion beams has several desirable attributes including precise control and uniformity of energy deposition, the ability to heat all types of samples (including insulators and conductors), large sample sizes compared with diagnostic resolution volumes, a benign environment for diagnostics (low debris and radiation background), high shot rates ($10\,\mathrm{h}^{-1}$ to $1\,\mathrm{s}^{-1}$) and options for multiple target chambers.

Our basic strategy [4] is to focus a high current beam at low to moderate ion particle energy (0.4–30 MeV) onto a thin foil target. The exact energy and ion mass are chosen such that the beam traverses the foil with energy around the Bragg peak [5]. The energy deposition is relatively uniform along the entire depth through the target, and precise measurements to determine the equation of state or other material properties can be carried out.

A parallel programme is being pursued in Germany in relation to the future GSI project FAIR [6–8]. In their approach, highly energetic heavy-ion beams (GeV/u) are used to study HEDP in a similar warm dense matter regime. In their approach, the beam deposits only a small fraction of its energy in the target, and the entrance and exit energies are nearly the same. Hence, their strategy will also lead to uniform energy deposition in the target, albeit with a technique quite different from the Bragg peak approach we adopt.

The key beam experiments in transverse and longitudinally beam-compressed brightness-preserving beam transport, as well as in beam acceleration, addressed the top-level question and have been conducted with both the near-term WDM and the long-term HIF applications in mind. We will first report on new results from these campaigns with intense beams, followed by specific advances towards WDM applications and HIF goals, respectively. For more details, the reader is referred to the Proceedings of the recent Heavy Ion Fusion Symposium [9, 10].

2. Longitudinal and transverse beam compression

We have completed the neutralized transport experiment (NTX), which demonstrates *transverse* beam compression when an otherwise space-charge-dominated ion beam was neutralized by plasma source(s) [11]. Figure 1 shows that a beam with an initial FWHM of 4 cm was compressed to 2.5 mm (FWHM) when one short section of plasma (plasma plug) was added to the entrance of a 1 m long drift section. When a second plasma source was implemented near the target area (volume plasma), the FWHM was further reduced to 2.1 mm. We were able to confirm that the residual space charge was indeed quite small by 'measuring' a fully neutralized beam (1.4 mm FWHM), which we obtained by a projection from the measured 4D phase space of the beam at entrance, using a newly developed moveable pinhole device.

This experiment was followed by the neutralized drift compression experiment (NDCX) in which an ion beam was *longitudinally* compressed by a factor of over 50 [12], figure 2. This was accomplished by applying a linear head-to-tail velocity 'tilt' to the beam, using a precisely tailored voltage waveform from an induction-bunching module and then allowing the beam to drift through a metre-long neutralizing background plasma.

In both the transverse and the longitudinal experiments, extensive 3D simulations, using the electromagnetic particle-in-cell code LSP [13], were carried out (figure 3). We have performed quantitative comparisons of the simulation results with our experimental data, and the agreements with experiments were excellent [12, 14]. A three-dimensional kinetic model for longitudinal compression with complete neutralization was developed, and the Vlasov equation was shown to possess a class of exact solutions for the problem [15]. Theories of beam–plasma interaction, with and without external focusing solenoids, have been studied extensively [16–18].

During the NDCX experiments, it was observed experimentally, and confirmed by theory and simulations, that a transverse defocusing resulting from the time-dependent induction buncher voltage causes the axial location of the

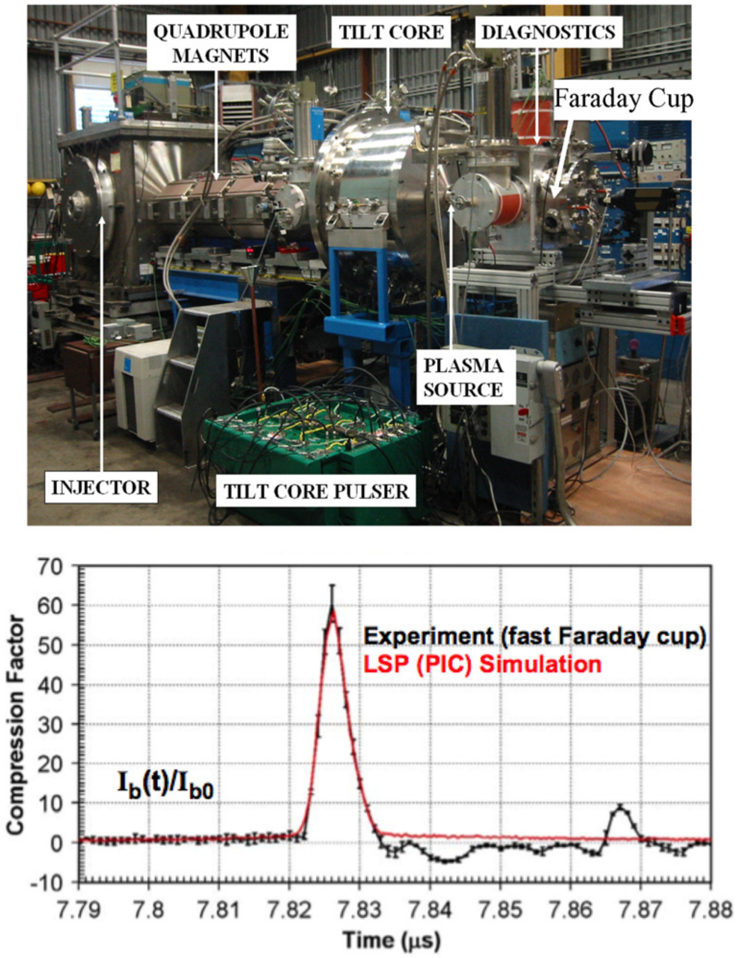

Figure 2. The NDCX experimental setup and demonstration of a >50-fold longitudinal compression of a K^+ beam at 300 keV and an initial current of 25 mA.

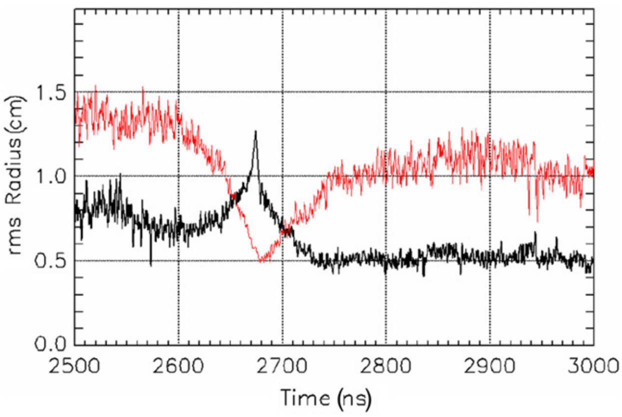

Figure 3. LSP particle-in-cell simulation of two scenarios of drift compression, (black) without and (red) with compensation for the defocusing in the gap of the bunching module. The convergence angle of the beam at the induction-bunching module was increased from 7.5 mrad (black) to 13.5 mrad (red).

transverse focus of the beam to shift relative to the longitudinal focus. By increasing the initial entrance angle of the beam to compensate for the defocusing effect, theory predicts that simultaneous transverse and longitudinal compression of the beam can be achieved [19]. This prediction has been confirmed in a very recent experiment.

In this experiment, the total beam compression (density increase) achieved is about 2000. The total compression required for WDM experiments is typically in the 10^5 range. Theory predicts that such compression factors are attainable by refinements in the induction voltage waveform, higher plasma densities and the final focussing using strong solenoids [20,21].

3. Beam transport and secondary electron effects

Quadrupole transport of space-charge-dominated ion beams has been a subject of intense studies, both theoretically and experimentally, for a number of years. Recent work has resolved a long-standing puzzle and demonstrates that strong chaotic resonances lead to the observed beam instabilities when the phase advance of the transport lattice is above 85° [22].

Another long-standing research area concerns the limits to transport imposed by beam instabilities of various types. Considerable progress has been made here as well. The beam equilibrium stability and transport code BEST was optimized for massively parallel computers and studies of

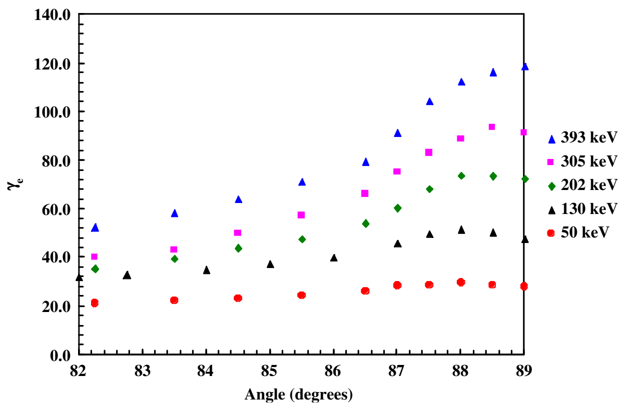

Figure 4. Ion-induced electron emission yields for K^+ ions at grazing angles.

the collective effects of 3D bunched beams [23] and the temperature-anisotropy instability [24] were carried out.

The main focus of our recent work has been on the effects of electron clouds and gas bursts, which are known to limit the performance of many major accelerator rings and may constrain the architectures of linacs being developed as drivers for HEDP and HIF. The accumulation of electrons in an ion beam can lead to brightness degradation and ultimately beam disruption.

An important source of electrons is from emission induced by ions impacting the beam tube near grazing incidence. We have measured the electron emission coefficient and the angle of incidence dependence for ions from 50 keV to 1 MeV [25, 26] (figure 4).

The trapping of electrons within an ion beam in a four-quadrupole magnet system [27] has been studied. A suppressor ring electrode (at the exit of the four-quadrupole system) and clearing electrodes (positively biased rings inserted into the drift regions between quadrupole magnets) provide the knobs to control electron flow from the end wall and the pipe wall into the beam region. Trapped electrons reduce the net beam potential by partial neutralization, which we measure with a new diagnostic, the retarding field analyzer (RFA) (figure 5). A small number of cold ions are generated within the beam by beam-impact ionization of the background gas and subsequently expelled by the net beam potential. The energy distributions of expelled ions are measured, from which we determine the peak potential of the beam and its variation over the beam pulse.

Finally, we have studied the interaction of the electron cloud with the beam, both experimentally and with simulations. We have developed self-consistent modelling of electrons in ion beams by adding electron and gas modules to the 3D beam-dynamics particle-in-cell code WARP [28]. These calculations have been facilitated by a pioneering application of adaptive mesh refinement (AMR) techniques to PIC simulations [29], which have increased the speed of WARP calculations by typically one order of magnitude and by three orders of magnitude in some extreme cases. Another major improvement has been the invention of a new algorithm for advancing electrons using large time-steps, based on an ‘interpolation’ between direct orbit calculation and a computation of the guiding-centre drifts [30]. An example of the WARP capability is shown in figure 6. With the suppressor electrode turned off, the beam is flooded with electrons which induce oscillations as they drift upstream through the last quadrupole. We find that the code accurately reproduces the frequency, wavelength and amplitude of the oscillations observed in the experiment [31].

Beam transport with solenoids has recently received much attention because of their favourable scaling for high line charge density at low particle energies [32], essential for both WDM and HIF applications. We have recently performed experiments on four-solenoid transport systems. With somewhat complex beam manipulations in this experiment, the measured beam envelope agrees with the calculations for a space-charge-dominated beam in vacuum [33].

4. Beam acceleration

Recent advances in induction cell technology and in long-pulse beam dynamics associated with radiography applications [34] have provided very important technical foundations for future HEDP and HIF drivers based on induction linacs. Multiple refinements in DARHT-II cell fabrication techniques, together with a rigorous testing program, have led to high confidence in the ability to build future machines with high reliability and robust operation.

With the induction technology safely in hand, we have ventured into a new concept, the pulse line ion accelerator (PLIA) [35] which is particularly suited to the WDM applications, but may also have applications for HIF. If proven successful, PLIA could provide significant cost reductions. In contrast to the induction cells with relatively bulky magnetic material, the PLIA acceleration module is a travelling wave structure based on a simple helical coil around an insulating vacuum tube, submersed in a dielectric medium and powered by a relatively low voltage pulse. An ion beam, with a particle speed nearly synchronous with the circuit speed of the structure, can be continuously accelerated throughout the entire path through the structure if the beam bunch is correctly timed to the phase of the voltage pulse. The final energy gain can be many times higher than the input voltage.

The 3D PIC simulations with WARP3D have predicted an efficient acceleration of bunched beams with PLIA. We have recently provided a rigorous experimental demonstration of the PLIA beam dynamics, by applying a voltage pulse with multiple oscillations on an initially long pulse with a constant energy. The travelling voltage pulse can cause different portions of the beam to be accelerated, decelerated, bunched or debunched. The longitudinal phase space was measured, using an energy analyzer, and the resulting complex structure was reproduced by the PIC code. Comparing the net beam energy gain with the input voltage, the experiment demonstrated a 7-fold multiplication [36] (figure 7). In these experiments, we observed an anomalous flashover at a very low field of $\sim$1 kV cm^{-1}. The causes and possible remedies of this flashover phenomenon are currently under investigation.

5. Near-term warm dense matter applications

We have identified a number of potentially significant beam/target experiments in the WDM regime at 2 eV

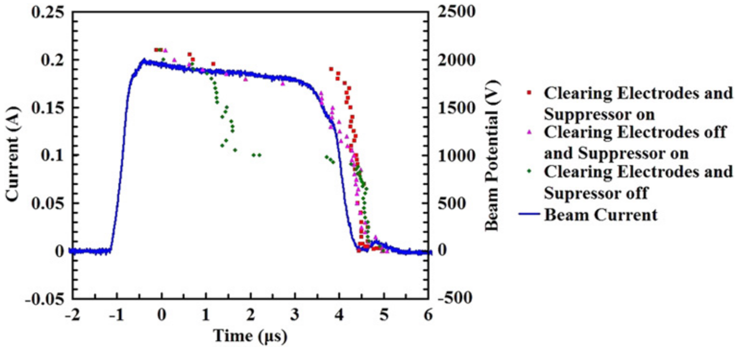

Figure 5. Beam potential variation during beam pulse.

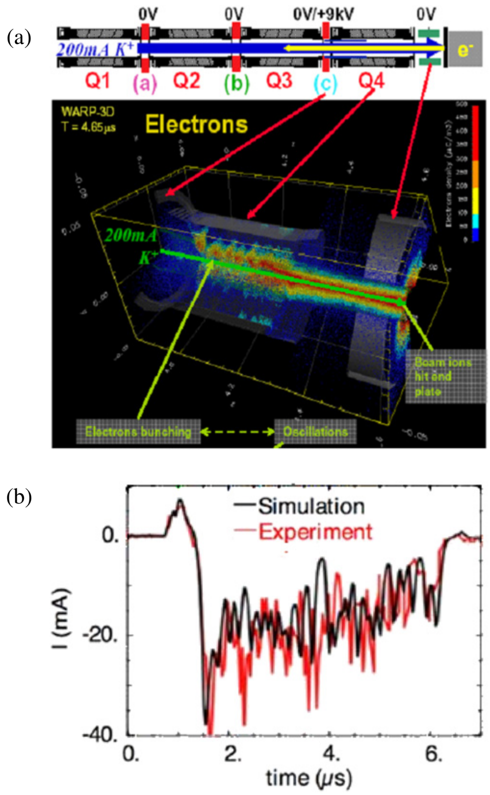

Figure 6. A 4-quadrupole system with an ion beam flooded by electrons from the end wall: (*a*) experimental layout and particle distribution around the fourth quadrupole from a WARP3D simulation and (*b*) current to the clearing electrode upstream of the fourth quadrupole-simulation and experiment compared.

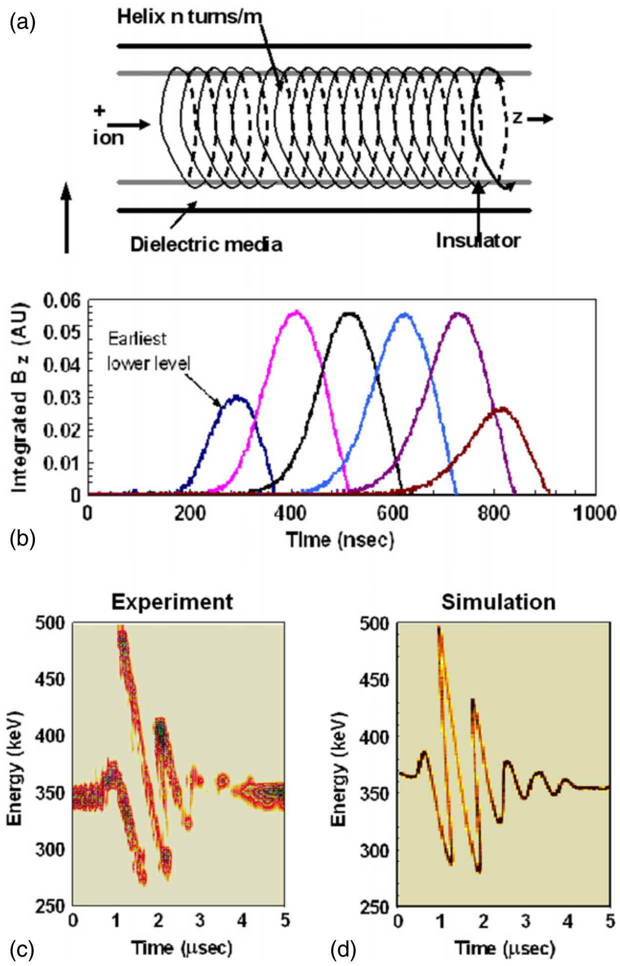

Figure 7. (*a*) PLIA is a simple current-carrying helix embedded in a dielectric medium. (*b*) A voltage applied to the input end travels down the helix at a circuit speed given by the inductance and the capacitance of the structure. (*c*) A long-pulse K^+ beam at 350 kV traverses a PLIA structure and develops a complex longitudinal phase space, in excellent agreement with simulations (*d*).

and below, which are accessible in the near-term with modest effort. They include beam-induced darkening of transparent material, measurements of target temperature and conductivity, positive–negative halogen ion plasma experiment at $kT \;>\sim\; 0.4$ eV (the conductivity of such a plasma may have similarities to semi-conductor), two-phase liquid–vapour metal experiments at $kT > 0.5$ eV and critical point measurements for metals at $kT > 1$ eV [37].

Some of the WDM experiments may be accessible in existing facilities with improvements in beam compression. We have also been performing design studies for a modest machine (NDCX-II) that will allow us to reach 2 eV, using a beam near the Bragg peak. The primary ions considered are Li at 2.8 MeV and Na at 24 MeV. The NDCX-II can be based either on induction linac technology or on the lower-cost PLIA architecture, if sufficient confidence on this new technology is obtained.

The basic beam requirements are the fluence on target per unit area and a pulse duration, which is short relative to the time scale for target hydrodynamic motion. We have constructed self-consistent driver point designs that will achieve the desired parameters. One example [38, 39] gives a 1 ns pulse with a fluence on target of 29 J cm^{-2}, and the predicted temperature is about 2 eV. It consists of an injector producing 100 mA and 300 ns Li^+ ions, which are accelerated to 2.8 MeV at an accelerating gradient of 1 MV m^{-1} (either PLIA or induction linac) in a transport system with 1.3 T solenoids. Using the pulse length, transverse and longitudinal emittances obtained from a self-consistent WARP simulation, calculations indicate that the beam can be compressed through a 3.4 m neutralized drift section with a final 15 T focusing solenoid to obtain a spot size of 0.4 mm. The whole beam-line, from source to target, is less than 10 m long.

6. Towards the HIF goal

While the emphasis during the past two years has been on the near-term WDM applications, we have made some progress in fusion-specific tasks also. Studies have continued on driver designs, with emphasis on modular approaches, with some tens of identical driver modules, each containing a single high current beam [40, 41]. This approach offers attractive short development paths towards the fusion driver.

We should also note that the WDM campaign can be seen as an essential step towards HIF. For final focussing in an HIF driver, it will prove far easier to learn how to control beam neutralization and beam–plasma effects than to try to ensure that no stray secondary electrons ever accumulate to more than 10^{-4} fraction of intense compressed beams in vacuum before final focus. So far success in learning how to compress and focus neutralized beams in plasma is going well, but much work remains. It will take until 2009 before we expect to produce 1 eV solid density plasmas using neutralized density compression techniques. For inertial fusion energy drivers, the transverse and longitudinal compression ratios (initial to final beam radius and initial to final pulse length) which have already been achieved are sufficient in dimensionless terms. The beam purveyances in the current accelerators being used are also sufficient for a driver. Beyond the needs for 1 eV solid targets (nominal peak 20 A at 500 keV), the remaining scale up to a driver is in beam voltage (500–1000 times), beam current (100 times) and the product of beam pulses and beam lines (100–400 times). The additional driver development programme will take an estimated 35 years and 10 times larger annual budgets than present.

Within the context of the conventional multi-quadrupole, multi-beam induction module approach to the HIF driver, a campaign begun several years ago to develop a compact driver-sized injector with merging beamlets has been successfully completed. In our experiment 119 argon ion beamlets at 400 keV beam energy were merged into an electrostatic quadrupole channel to form a single beam of 70 mA as designed. The normalized emittance of the merged beam was measured to be in the range of 0.7pi mm-mrad, in good agreement with PIC simulations and meeting driver requirements [42].

Space-charge-dominated beam physics experiments relevant to long-path accelerators were carried out on the University of Maryland Electron Ring, where multi-turn commissioning has thus far resulted in the circulation of up to 50 turns with a record-breaking beam in terms of space charge intensity in a ring [43]. The Paul trap simulator experiment (PTSX) uses time-dependent quadrupolar voltages in the lab frame to simulate propagation through a kilometre-long magnetic alternating-gradient (AG) transport system in the beam frame. The conditions for emittance growth and generation of halo particles have been ascertained [44].

Acknowledgments

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